difficult to observe and model. Advancement of AABW research represents a significant technological challenge to field and computer oceanographers.

Summary

The ocean is cold. Its average temperature of 3.5°C is far colder than the warm veneer capping much of the ocean. Waters warmer than 10°C amount to only 10% of the total ocean volume; about 75% of the ocean is colder than 4°C. Along the seafloor the ocean temperature is near 0°C. The cold bottom water is derived from Southern Ocean, the ocean belt surrounding Antarctica. Sea water at its freezing point of -1.9°C is formed in winter over the continental shelf of Antarctica. Where the salt content of shelf water is high enough, roughly 34.61‰ (parts per thousand) the water is sufficiently dense to descend as convective plumes over the continental slope into the adjacent deep ocean. In so doing Antarctic Bottom Water is formed. It is estimated that on average between 10 and $15\times10^6\,m^3$ of Antarctic bottom water forms every second! Antarctic Bottom Water spreads away from Antarctica into the world oceans, chilling the deep ocean to temperatures near 0°C. Bottom water warms en route on mixing with warmer overlying waters. Cold winter water also forms in the Greenland and Norwegian Seas of the northern North Atlantic. This water ponds up behind a submarine ridge spanning the distance from Greenland to Scotland. This water overflows the ridge crest into the ocean to the south. As the overflow water mixes with warmer saltier water during descent into the deep ocean, it results in a warmer, more saline water mass than Antarctic Bottom water. The Greenland and Norwegian Sea overflow water forms the densest component of the water mass called North Atlantic Deep Water and is estimated to form at a rate of around $8\times10^6\,m^3\,s^{-1}$. The overflow water stays in contact with the seafloor until the northern fringes of Antarctic Bottom Water encountered in the North Atlantic near 40°N, lifts it to shallower levels.

See also

Antarctic Circumpolar Current. Polynyas. Rotating Gravity Currents. Sub Ice-shelf Circulation and Processes. Weddell Sea Circulation.

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BRAZIL AND FALKLANDS (MALVINAS) CURRENTS

A. R. Piola, Universidad de Buenos Aires, Buenos Aires, Argentina
R. P. Matano, Oregon State University, Corvallis, OR, USA

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Introduction

The zonal component of the mean prevailing winds, low latitude easterlies and mid-latitude westerlies induce anticyclonic[1] upper ocean circulation pat-

[1] Clockwise in the northern hemisphere and counter-clockwise in the southern hemisphere.

terns referred to as subtropical gyres. The latitudinal rate of change of the Earth's rotation induces a zonal asymmetry in these gyres, and intensifies the flow near the western boundaries. The Brazil Current is the western limb of the subtropical gyre that carries warm and salty waters poleward along the continental slope of South America (**Figure 1**). Near 39°S the Brazil Current collides with a northward branch of the Antarctic Circumpolar Current (ACC), the Malvinas (Falkland) Current, which transports cold and relatively fresh subAntarctic waters equatorward. The collision between these

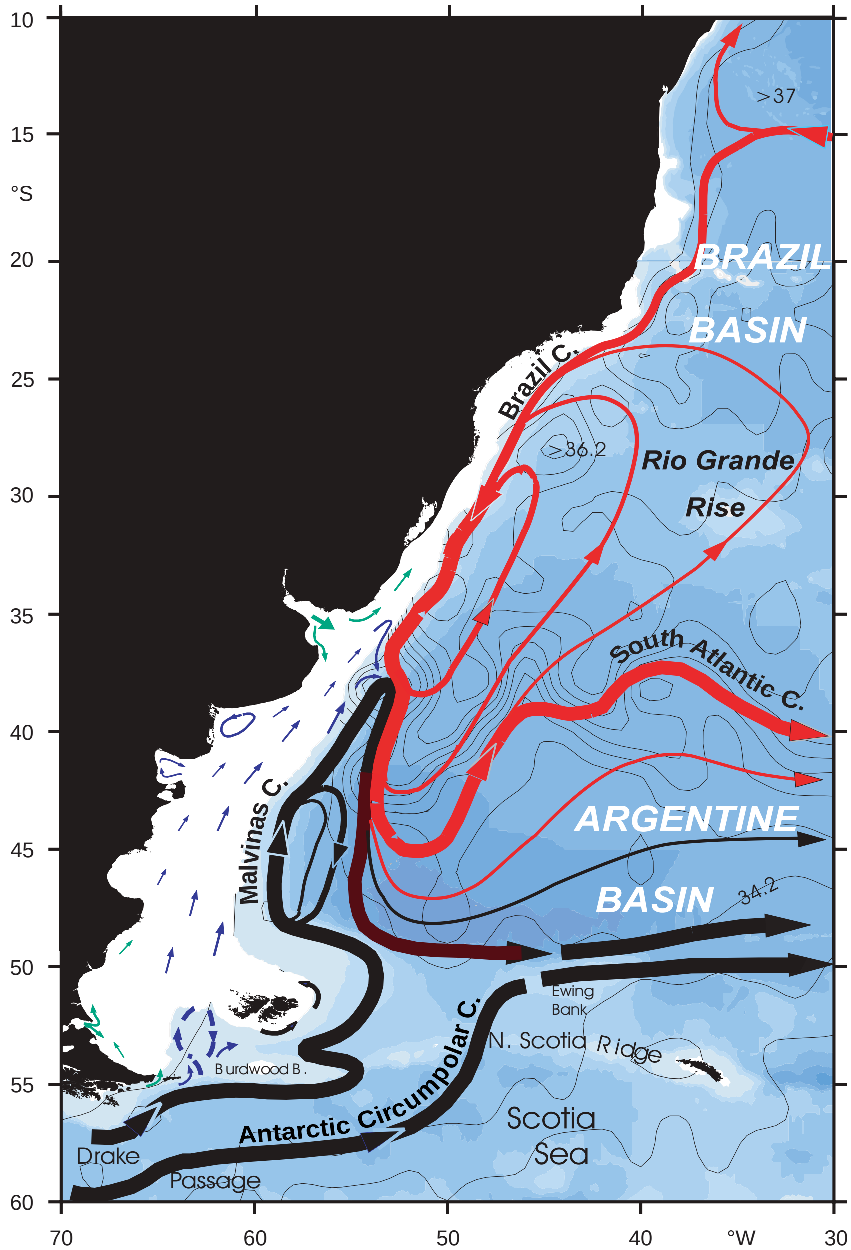

Figure 1 Schematic diagram of the upper layer circulation of the South Atlantic western boundary currents. Black lines are used for the Antarctic and subAntarctic water flows, associated with the Antarctic Circumpolar Current and the Malvinas Current. Red lines are used for the flow of the subtropical waters carried by the Brazil Current. Over the Patagonian continental shelf the arrows represent the mean surface currents. The thin contour lines show the salinity field at 200 m depth that was used to infer part of the circulation scheme. The salinity at 200 m ranges from 34.2 south of the Confluence to 37 near 15°S. A sharp salinity front develops at the Brazil/Malvinas Confluence and extends in a meandering fashion towards the ocean interior where it marks the South Atlantic Current. The background shading represents the bottom topography with darker shading corresponding to deeper waters. The deepest area in the southern Argentine Basin is the Argentine Abyssal Plain where depth is greater than 6000 m. Major topographic features and currents cited in the text are labeled.

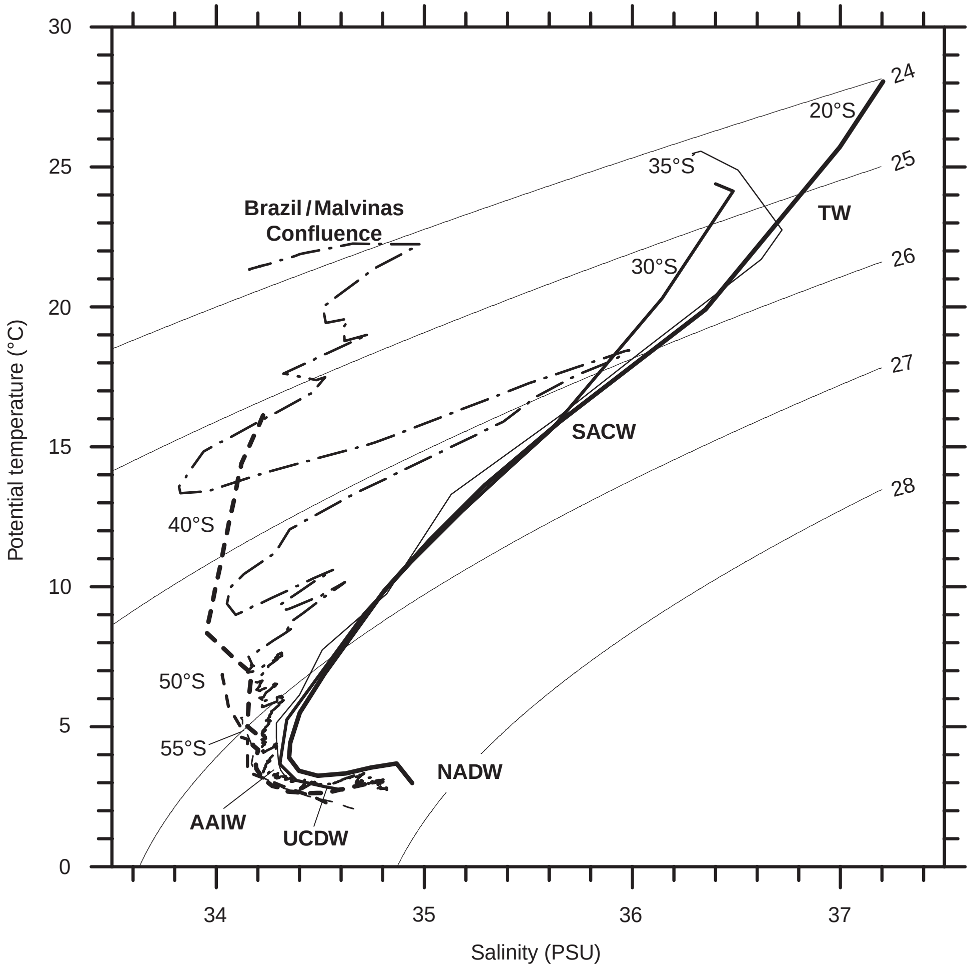

Figure 2 Potential temperature–salinity diagrams from hydrographic stations collected during austral summer along the paths of the Brazil Current (from 20°S in the Brazil Basin to 35°S, solid lines) and along the Malvinas Current (from 55°S in the northern Drake Passage and 40°S, dashed lines). These stations are located between the 1000 m and 2000 m isobaths near the cores of the western boundary currents. Also included is a station from the Brazil/Malvinas Confluence after separation from the western boundary (dashed-dotted line). Constant density anomaly (σ_θ in units of km m^{-3}) lines are included. See **Figure 3** for abbreviations.

distinct water masses generates one of the most energetic regions of the world ocean: the Brazil/Malvinas Confluence (BMC). This article reviews *in situ* and remote observations and the results of numerical simulations that describe the mean structure and time variability of the Brazil and Malvinas Currents and the frontal region that they generate.

Water Masses

The western South Atlantic has been referred to as the 'cross-roads of the world ocean circulation', because it hosts water formed in remote areas of the world, and brought into this region by the large-scale ocean circulation. This meeting of water masses generates a highly complex vertical stratification structure. In the upper ocean, this structure is dominated by the confluence of subtropical and sub-Antarctic waters associated with the opposing flows of the Brazil and Malvinas Currents. In the deep ocean, the vertical stratification structure is dominated by contributions from deep and bottom waters from the North Atlantic, South Pacific, and Antarctic regions.

To illustrate the water mass structure of the upper layer of the western South Atlantic, **Figure 2** shows a diagram of potential temperature[2] versus salinity (θ–S) from summer stations collected within the cores of the Brazil and Malvinas Currents (1000–2000 m depth range). From 20°S to 35°S, **Figure 2** illustrates the θ/S characteristics associated with the water masses advected by the Brazil Current and, from 55°S to 40°S, with those advected

[2] θ is the temperature of a water parcel raised adiabatically to the sea surface, thus removing the effect of pressure.

by the Malvinas Current. In addition, **Figure 2** also shows the θ–S diagram of a hydrographic station collected downstream from the separation of both boundary currents from the continental margin (e.g. within the core of the BMC).

Upper Ocean

The upper portion of the water mass carried poleward by the Brazil Current is referred to as Tropical Waters (TW), and is characterized by high potential temperature ($\theta > 20°C$) and salinity ($S > 36$ PSU, **Figure 2**). The high temperatures of the TW are due to heat gained from the atmosphere at low latitudes, while the high salinities are due to freshwater losses at mid-latitudes. The upper portion of the Brazil Current is also characterized by the presence of relatively thin low salinity layers capping the TW structure (e.g. the 35°S curve in **Figure 2**). These low salinity layers are thought to be caused by mixing between TW and shelf and river waters. Below the TW, but still within the Brazil Current, there is a sharp thermocline and halocline (see the quasilinear θ–S relation in the 20–10°C temperature range) that is referred to as South Atlantic Central Water (SACW). The SACW shows a very stable θ–S pattern with only minor variations induced by winter sea–air interactions near the southern limit of the Brazil Current.

The upper layer of the Malvinas Current (i.e. the curves corresponding to 40° and 50°S in **Figure 2**) is substantially colder ($\theta < 15°C$) and fresher ($S < 34.2$ PSU) than the corresponding layer of the Brazil Current. These properties reflect the sub-Antarctic origin of the Malvinas waters. In the northern portion of the Drake Passage, the source for the Malvinas transport, the surface temperature is close to 4°C and increases northward up to 16°C at the latitude where the Malvinas separates from the continental boundary (~ 40°S). Although the sub-Antarctic waters of the Malvinas Current and the SACW of the Brazil Current thermocline occupy the same density range ($\sigma_\theta \sim 25.5$–$27.0\,\mathrm{kg\,m^{-3}}$) they have very different thermohaline characteristics and the convergence of these water masses, in the BMC, leads to the formation of alternate layers of sub-Antarctic and subtropical water. These intrusions are referred to as interleaving or fine-structure (see station at BMC, **Figure 2**).

Antarctic Intermediate Water

The water mass structure of the Brazil Current at intermediate depths (700–1000 m) is dominated by the presence of Antarctic Intermediate Water (AAIW). The AAIW, characterized by a salinity minimum ($S < 34.3$ PSU), has contributions from the coldest and densest ($\sigma_\theta \sim 27.3\,\mathrm{kg\,m^{-3}}$) member of the southern hemisphere Subpolar Mode Water or SubAntarctic Mode Water (SAMW), which originates from deep winter convection along the Sub-Antarctic Zone. The Malvinas Current carries newly formed AAIW and SAMW into the Argentine Basin. Data collected during the austral winter show that, as the AAIW/SAMW enter into the Argentine Basin from the south, they are exposed to the atmosphere and are subject to further modification by local air–sea interactions. South of the BMC, the AAIW/SAMW are less salty ($S < 34.1$ PSU) than within the Brazil Current (**Figure 2**) and these lateral property gradients across the BMC induce interleaving. Similarly to the upper layer flow, the temperature of the AAIW core increases from 3°C, at the Drake Passage, to 3.5°C at 40°S.

It is interesting to note that although on average the AAIW must spread northward (away from the region of formation), direct current observations at 28°S, and close to the continental margin indicate that, in the subtropical basin, the AAIW follows the upper ocean anticyclonic gyre, and flows southward below the Brazil Current. After leaving the continental boundary the AAIW turns into the subtropical gyre, where vertical and lateral mixing increase its salinity and decrease its dissolved oxygen concentration. The water mass resulting from this recirculation process is known as recirculated AAIW.

Deep and Abyssal Water

The deep layers of the western South Atlantic show a variety of water masses which are depicted by their properties in **Figure 3**. Below the Brazil Current, there is the poleward flow of North Atlantic Deep Water (NADW), which is the primary source of ventilation underneath the main thermocline. The NADW originates at the high latitudes of the North Atlantic Ocean, from where it spreads southward along the continental slope of the American continent. At 30°S the NADW is characterized by relatively high potential temperature ($\theta \sim 3°C$), salinity ($S \sim 34.8$ PSU), and dissolved oxygen ($O_2 \sim 250$ $\mu\mathrm{mol\,kg^{-1}}$). Below 800–1000 m Circumpolar Deep Water (CDW) flows northward within the Malvinas Current. Although the nutrient-rich CDW originates from NADW, mixing along its path around the Antarctic Continent leads to decreased concentrations of oxygen and salinity. Consequently, although CDW is still identified by a relative salinity maximum, its salinity at the core still is lower than that of NADW. In the western Argentine Basin the NADW splits the CDW into two layers: the upper

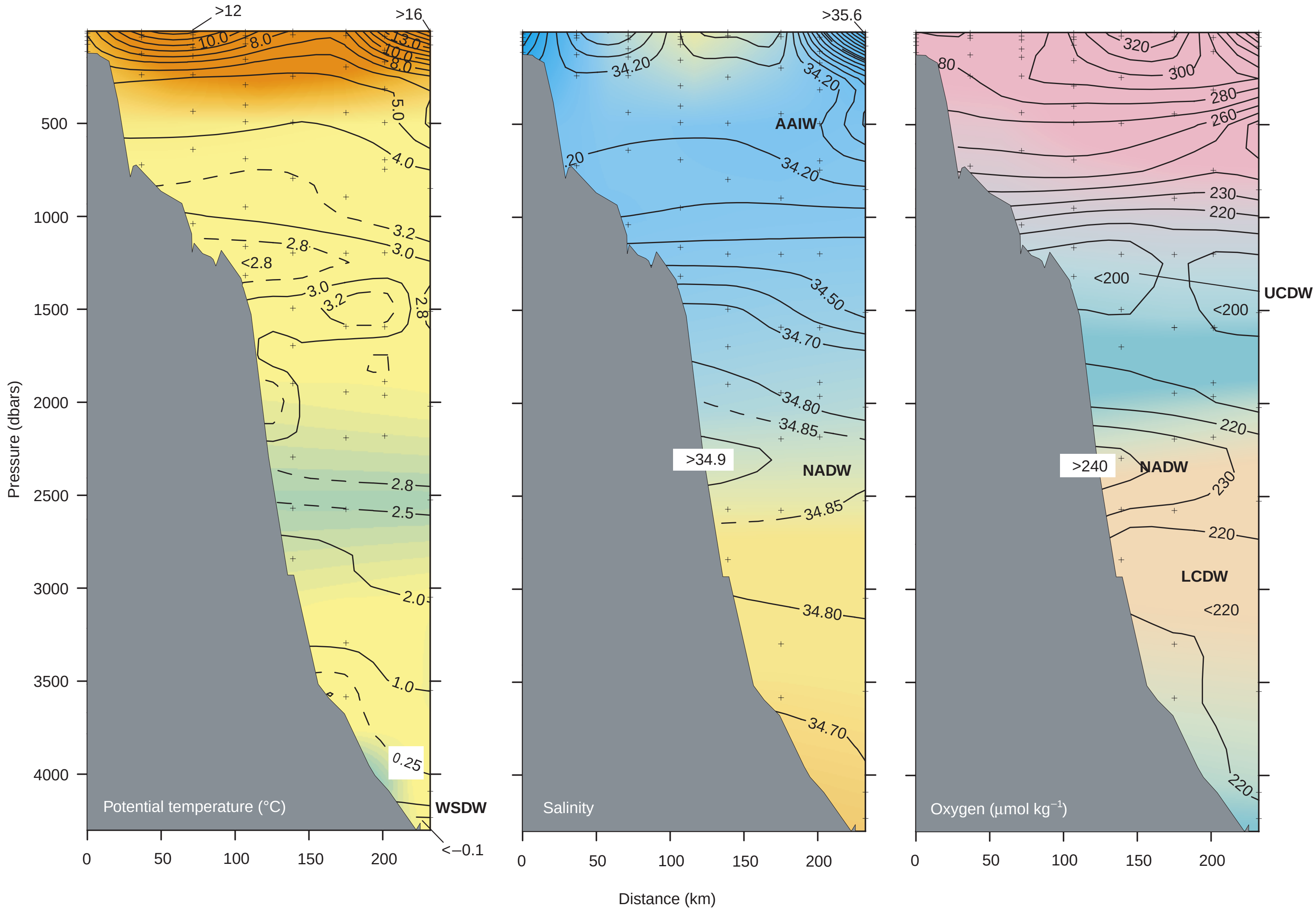

Figure 3 Late winter vertical potential temperature (°C), salinity (PSU), and dissolved oxygen (μmol kg^{-1}) sections from the Brazil/Malvinas Confluence near 38°S. Water masses identified by property extrema are labeled as follows: TW, Tropical Water; SACW, South Atlantic Central Water; AAIW, Antarctic Intermediate Water; UCDW, Upper Circumpolar Deep Water; NADW, North Atlantic Deep Water; LCDW, Lower Circumpolar Deep Water; WSDW, Weddell Sea Deep Water.

CDW (UCDW) and the lower CDW (LCDW). The latter are identified by two minima in dissolved oxygen above and below the high salinity, oxygen-rich NADW. The existence of two separate oxygen minimum layers is apparent north of 50°S (**Figure 3**). From the Drake Passage the UCDW flows into the Argentine Basin closely following the 1000–1500 m isobaths. At 40°S the UCDW is characterized by deep ($\sim$ 1400 m) temperature ($\theta < 2.9$°C) and dissolved oxygen minima ($O_2 < 200\,\mu mol\,kg^{-1}$). The LCDW is the densest water flowing eastward through Drake Passage. It enters the Argentine Basin over the Falkland Plateau and primarily east of Ewing Bank, flows westward along the escarpment located at 49°S and continues northward along the continental slope of the Argentine Basin at 3000–3500 m depth (**Figure 3**).

The abyssal waters of the southern hemisphere oceans are derived from southern high latitudes and are generally referred to as Antarctic Bottom Water. In the western South Atlantic the bottom waters are cold ($\theta < 0$°C), oxygen-rich ($O_2 \sim 225\,\mu mol\,kg^{-1}$), and nutrient-rich. These abyssal waters are denser and colder than the densest water found in the Drake Passage and must derive from the Weddell Sea. Underneath the continental ice shelves of the southern Weddell Sea the densest water mass of the world ocean is formed, but it is the Weddell Sea Deep Water (WSDW), a product of mixing between the CDW and the Weddell Sea Bottom Water, which flows northward around the Scotia Trench and enters into the Argentine Basin as an abyssal western boundary current.

Circulation

Brazil Current

The Brazil Current originates along the continental slope of South America, between 10° and 15°S, through a branching of the westward-flowing South Equatorial Current. The northern branch of the South Equatorial Current forms the North Brazil Current, and represents a loss of upper layer mass from the South Atlantic to the North Atlantic. The southern branch forms the Brazil Current, the western boundary current of the subtropical South Atlantic Ocean. A substantial amount of the southward upper ocean flow occurs on the outer continental shelf of Brazil. Although the term Brazil Current usually refers to the flow within the upper 1500 m, there is evidence that the current may extend well beyond that depth. In fact, hydrographic observations suggest that the AAIW layer is also part of the southward-flowing western boundary current. Direct current measurements off southern Brazil also reveal that although the upper layer flow of the South Equatorial Current reaches South America near 15°S, at intermediate depths the bifurcation shifts south of 24°S. The addition of recirculated AAIW to the southward flow would contribute to the increase of volume transport of the Brazil Current observed south of approximately 28°S.

Geostrophic calculations, and a few direct current measurements of the Brazil Current transport, yield a value of only about 4–6 Sv, between 10 and 20°S, and this increases to about 20 Sv at 38°S, near the BMC. The rate of transport increase for the Brazil Current is comparable to that of the Gulf Stream. The increase of the Brazil Current's transport is partially associated with a tight recirculation cell near the western boundary and, perhaps, the addition of intermediate waters near 25°S. *In situ* observations, between 20° and 28°S, have shown that the poleward increase of volume transport of the Brazil Current to 16 Sv is associated with a deepening of the current from 100 m to 600 m. While the discussion on the Brazil Current's transport has focused on the upper 1000 m, there are also important poleward, western boundary undercurrents below the thermocline. At 27°S, for example, the core of the southward-flowing NADW ($S > 34.94$ PSU) is found at approximately 2000 m and east of the upper ocean jet. If this undercurrent is included in the transport calculation then the southward volume transport relative to a deep reference level is close to 11 Sv at 27°S, and increases southward to 70–80 Sv at 36°S. Although this estimate may include some southward recirculation of subAntarctic water and CDW from the Malvinas Current it is, nevertheless, much larger than previous values.

Malvinas Current

In contrast with the Brazil Current the Malvinas Current has a strong barotropic component (i.e. the density stratification is more closely related to the pressure field than to the temperature and salinity variations). This characteristic is typical of waters of subpolar origin, which have less thermohaline stratification than waters of tropical or subtropical origin. Consequently the Malvinas Current is strongly steered by the bottom topography as it flows along the continental slope of South America. Hydrographic observations suggest that most of the water flowing eastward along the SubAntarctic Front, in the northern Drake Passage, loops northward to form the Malvinas Current. Downstream from the Drake Passage, a portion of the upper layer flow deflects northward west of Burdwood Bank. The remainder of the northern ACC jet deflects northward through a gap located east of Burdwood Bank, where bottom depth is >1700 m. Both branches rejoin north of Burdwood Bank. Deeper and denser water can only flow northward depending on the complex bottom topography. Most of the flow deflects westward following the bottom topography of the deep chasm, which separates the north Scotia Ridge and the Falkland Plateau. Near 48°S the current is well organized, closely following the bottom topography, and appears to have little spatial variability.

The Malvinas Current extends from the sea surface to the ocean floor. From 50° to 40°S maximum surface speeds ($>0.7\,\mathrm{m\,s^{-1}}$) are observed over the 1000 m isobath, decreasing at either side of the jet. Within the northward-flowing current, the AAIW, and the oxygen-poor/nutrient-rich UCDW core, are also observed close to the 1000 m isobath – suggesting a coherent flow throughout the water column. This confirms the idea of a substantial barotropic contribution to the flow.

Relative geostrophic volume transport estimates of the Malvinas Current vary between 10 and 12 Sv. However, mass conservation arguments for the cross-isobath component in the BMC suggest that the total flow (e.g. barotropic + baroclinic) must be substantially higher (~ 70 Sv). These high estimates are also required if most of the waters within and north of the SubAntarctic Front of the northern Drake Passage are included in the Malvinas Current. Recent direct current observations near 41°S lead to a mean volume transport estimate of about 35 Sv, with a barotropic contribution of approximately 50%. However, these observations may be north enough to miss part of the flow that recirculates southward as the Malvinas Return Current (**Figure 1**). Along the southern edge of the Argentine Basin there is a westward flow, of approximately 8 Sv, of cold water derived from the Weddell Sea. A small portion of the Antarctic contribution (~ 2 Sv) is relatively new WSDW, while the remaining value of 6 Sv corresponds to WSDW recirculated within a bottom cell whose western branch is observed to the east of the Malvinas upper layer jet (**Figure 3**).

Brazil/Malvinas Confluence

Near 38°S, close to the region of highest volume transport, the Brazil Current meets the northward-flowing Malvinas Current. This head-on collision causes the current systems to separate from the western boundary forming a large, quasi-stationary, meander that extends southward to about 45°S. The encounter between these distinct western boundary currents creates an intense thermohaline front known as the Brazil/Malvinas Confluence. Surface velocities along the frontal jet exceed $1\,\mathrm{m\,s^{-1}}$, and there are indications that the current extends vertically beyond the 4000 m depth. Quasi-continuous temperature-salinity profiles reveal signatures of intense mixing of subAntarctic waters and subtropical waters along the front. This intensive mixing extends to the deep waters where NADW-CDW interleaving is also observed. Observations of relatively high salinity ($S > 34.8$ PSU), oxygen-rich ($O_2 > 210\,\mu\mathrm{mol\,kg^{-1}}$) deep waters below the Malvinas Current, show that the NADW found underneath the Brazil Current flows poleward beyond the separation point of the upper layer, suggesting a decoupling of the deep and upper western boundary currents.

The collision of the Brazil and Malvinas currents spawns one of the most spectacular eddy fields of the global ocean (**Figure 4**). The generation of warm- and cold-core eddies at either side of the front have led to mesoscale variability only matched by the offshore extensions of the Gulf Stream, the Kuroshio, and the Agulhas Current. The conspicuous precursor to the production of warm-core eddies is the anomalous poleward migration of the Brazil Current, which forms a complicated intrusive pattern leading to a set of meanders and rings sometimes referred to as the intrusion eddy. The sea surface temperature anomalies of these rings can be as large as 10°C and they occur over timescales of approximately 2 months. Hydrographic observations show that the eddies in the BMC region are vertically coherent, with signatures down to several thousand meters. These eddies are an important mechanism for the meridional transfer of salt and heat. Warm-core rings detached from the Brazil Current retroflection are frequently entrained into the subantarctic gyre. Likewise, cold filaments or rings detached from the Malvinas Current are frequently driven onto the recirculation cell that dominates the south-western portion of the subtropical gyre.

Besides the mesoscale variability associated with the formation of eddies and meanders, the variability of the BMC system also has distinctive peaks at semi-annual and annual periods. While the semi-annual variability in the Brazil Current is very small it increases to nearly half the magnitude of the annual signal in the Malvinas Current. It is thought that the semi-annual component of the Malvinas Current variability relates to a similar component in the wind forcing over the Southern Ocean. The annual component of the variability in the south-western Atlantic is dominated by the large meridional excursions of the BMC front. Satellite-derived sea surface temperature and sea surface height anomalies revealed that the latitude of the location of the BMC front has a tendency to move north during the austral winter (July–September) and south during the austral summer (January–March).

Since the location of the BMC is thought to depend on the mass transports of the two western boundary currents the seasonal displacements of the confluence may reflect relative variations of those transports. Numerical simulations of this region (e.g. **Figure 5**) indicate that the transport of the Brazil Current follows the annual evolution of the wind stress curl over the subtropical basin, reaching a maximum during the summer (when the BMC is at its southernmost position) and a minimum during the winter (when the confluence moves farther north). It is not known whether the Malvinas Current makes any significant contribution to these seasonal oscillations. Although it is known that the northern branch of the ACC, which feeds the Malvinas transport, has a clearly defined annual signal at the Drake Passage, *in situ* and remote observations have failed to identify any clear seasonal variation at mid-latitudes.

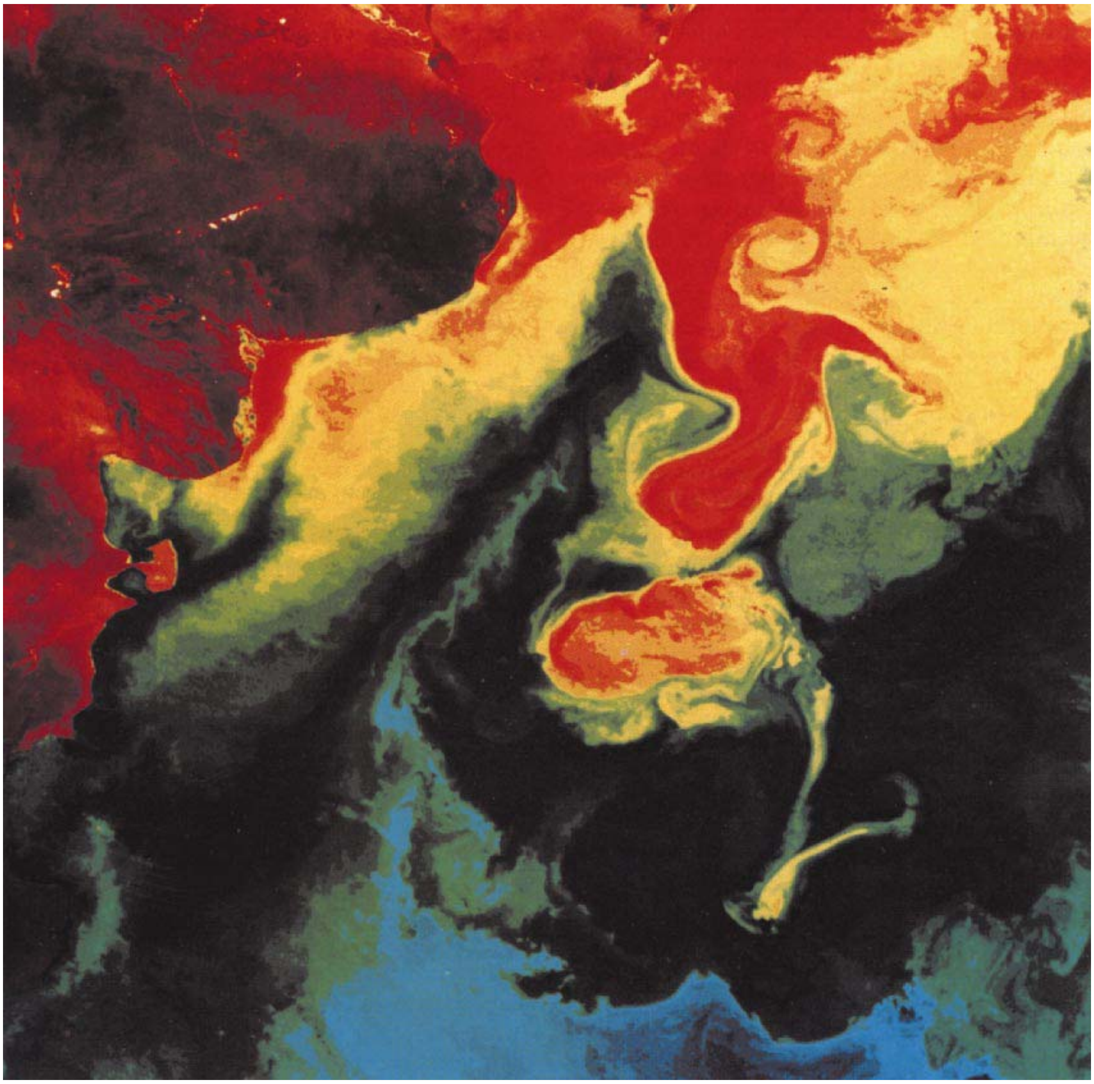

Figure 4 Advanced very high resolution radiometer image of the Brazil/Malvinas Confluence at a time when the Brazil Current was in its southward extension and a large anticyclonic (warm) eddy was being formed. Warmest surface waters (approximately 25°C) are coded in red. The surface temperature decreases are color-coded through yellow and green; the dark blue areas show the coldest waters advected northward by the Malvinas Current (approximately 9°C). (Figure courtesy of O. Brown, R. Evans, and G. Podestá, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami and Estación HRPT Alta Resolución, Servicio Meteorológico Nacional, Argentina.)

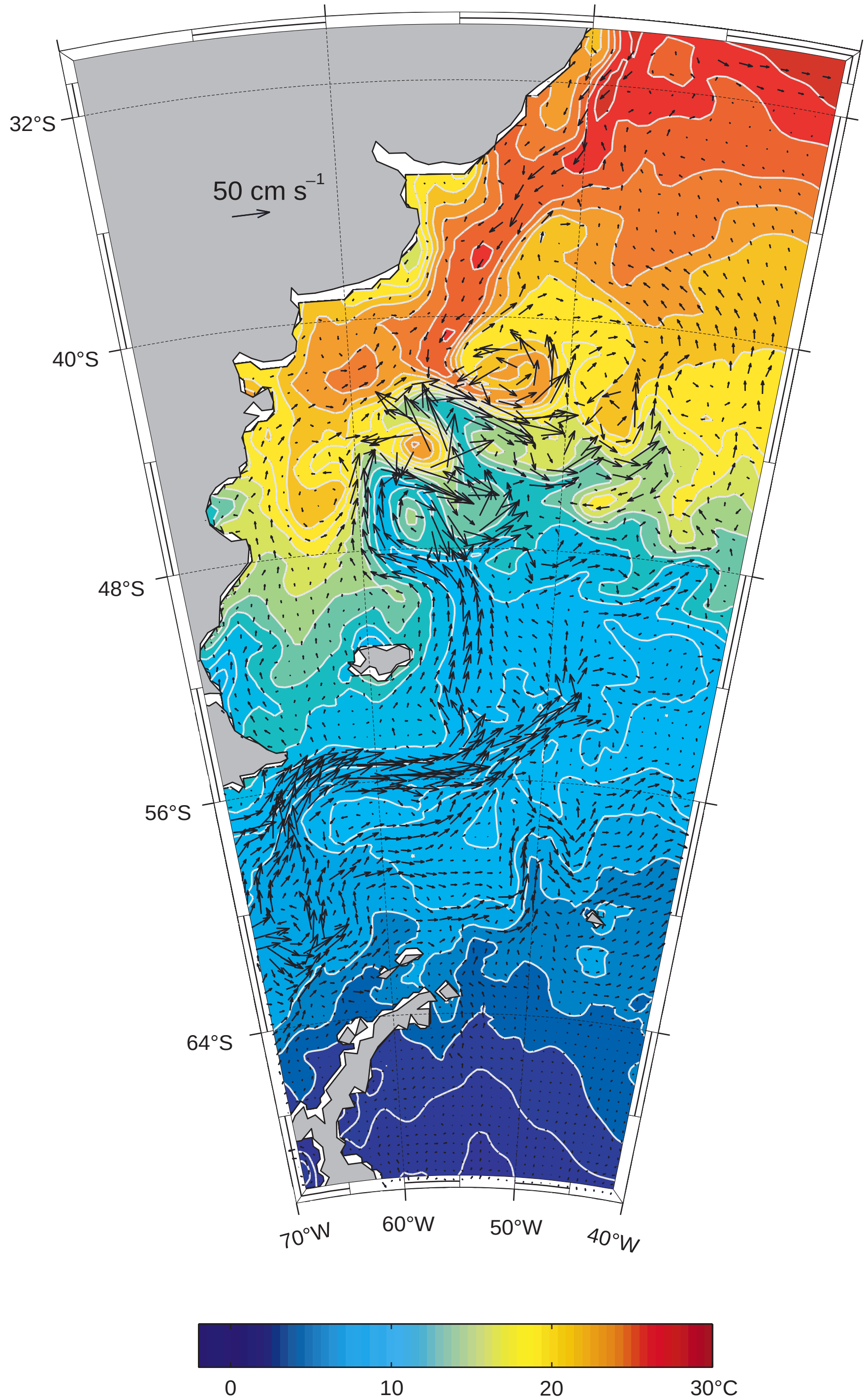

Figure 5 Snapshot of the upper ocean circulation in the western South Atlantic as simulated by the Parallel Ocean Climate Model (POCM). The color fields correspond to sea surface temperatures and the arrows to velocity vectors. The velocity scale is included in the figure. (Figure prepared courtesy of E. Beier.)

Acknowledgments

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See also

Abyssal Currents. Antarctic Circumpolar Current. Current Systems in the Atlantic Ocean. Current Systems in the Southern Ocean. Elemental Distribution: Overview. Intrusions. Mesoscale Eddies. Ocean Circulation. Regional and Shelf Sea Models. Satellite Altimetry. Satellite Remote Sensing of Sea Surface Temperatures. Upper Ocean Time and Space Variability. Water Types and Water Masses.

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BREAKING WAVES AND NEAR-SURFACE TURBULENCE

S. A. Thorpe, School of Ocean and Earth Science, Southampton, UK

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Introduction

The breaking of waves on the sea surface creates turbulence in the water. This article is about wave breaking in deep water where the waves and turbulence are not affected by the presence of the sea bed; it does not describe turbulence generated by waves breaking on beaches or by the bores within the surf zone at the edge of the sea (*see* **Beaches, Physical Processes Affecting**).

The processes of wave breaking and turbulence generation are very important in the transfer of momentum and exchange of heat and gases between the atmosphere and the oceans, in generating and dispersing bubbles, oil droplets or surface films into the body of the 'mixed' layer, and in renewing the sea surface with subsurface water; breakers disrupt the cold surface skin of the ocean (e.g. *see* **IR Radiometers**). Nevertheless, the state of knowledge of wave breaking and its consequent turbulence is profoundly unsatisfactory. The present incomplete knowledge of breaking and turbulence hinders progress in understanding vitally important processes, such as those of gas transfer and the dispersion of pollutants from the water surface. The subject is, however, presently one of some activity, made possible only in the last two decades of the last century by the development of suitable sensors and methods of mounting them in the often violent and hostile environment of the sea surface, and future progress can be expected.

The turbulence generated by breaking waves will coexist with, and interact with turbulence generated in other ways in the upper ocean, such as Langmuir circulation (which, in view of its instability, may have turbulent characteristics; *see* **Langmuir Circulation and Instability**) and that produced by shear or convection in the mixed layer. These interactions are not presently understood and will not be discussed further in this article.

Breaking Waves

Three related kinds of wave breaking occur in deep water and lead to turbulence in the water. These are:

1. a spilling breaker in which water near a wave crest entrains air leading to a white cap on or slightly forward of a wave crest;
2. a plunging breaker, the more dramatic form of breaking observed commonly on the sea shore, in which a jet of water moves forward from near the top of a wave and falls, trapping and entraining into the water a volume of air;
3. the formation of capillary ripples on the forward face of a steep, short (typically 0.1 m wavelength) surface-gravity wave. In their most extreme form the ripples may lead to entrainment of air into the water. (*see* **Surface, Gravity and Capillary Waves**).